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INVESTIGATION ON START-UP CHARACTERISTICS OF CRYOGENIC HEAT PIPES

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ABSTRACT

Heat pipe is a device which transfers heat from one location to another with a small temperature gradient. Application includes use of cryogenic heat pipe in cooling infrared sensors, laser systems, cryocoolers, thermal control large superconducting magnets and tumor surgery. This paper deals with transient behavior of cryogenic heat pipes with wire mesh and axial grooved wick using nitrogen and oxygen as working fluid. A special liquid nitrogen cryostat has been designed and developed for evaluating the transient behavior of heat pipes at 77 K when the condenser portion is connected to the cold sink externally. In this study, the start-up characteristic of heat pipes is experimentally investigated.

Keywords: cryogenic heat pipe, start up behavior.

INTRODUCTION

A heat pipe is a self-contained structure, which achieves very high thermal conductance by means of capillary circulation. It utilizes the latent heat of the vaporized working fluid for transfer of heat. As a result, the effective thermal conductivity is several orders of magnitudes higher than that of the good solid conductors. As illustrated in Figure-1 a heat pipe consists of three distinct regions: an evaporator or heat addition region, a condenser or heat rejection region, and an adiabatic region.

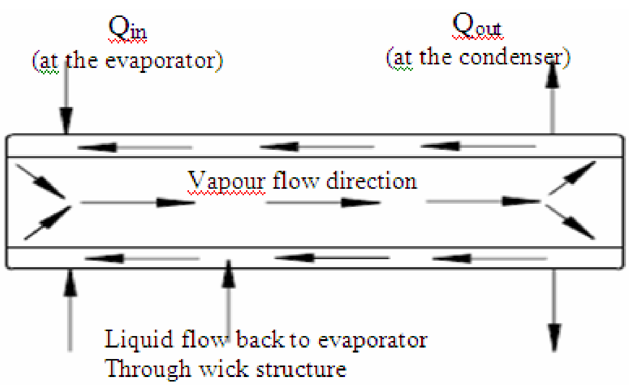

Figure-1. Schematic of a typical heat pipe operation.

Generally an effective wick requires small surface pores for large capillary pressure, large internal pores (in the direction normal to the liquid flow) for minimal liquid-flow resistance, and an uninterrupted highly conductive heat-flow path across the wick thickness for a small temperature drop.

The performance of a wrapped-screen wick cryogenic heat pipe is less than that of an axial groove wick heat pipes. This could be attributed to the fact that the temperature drop across wrapped screen wick is large due to low thermal conductivity of cryogenic liquids. On the other hand in axial groove wick, highly conductive metal fins assure a low resistance for heat flow across the wick. One comparison of this type was made between an axially grooved heat pipe and one with a homogeneous wick, Joy [1]. Using oxygen as the working fluids, a greater than twofold increase in the performance was predicted for the grooved heat pipe due to reduction in the viscous pressure drop of the liquid in the wick.

A detailed theoretical analysis for determining various pressure drops and performance of heat pipes has been presented by Cotter [2]. Many investigators (Armaly [3], Foster and Murrary [4], Zang [5], Edelstein and Kosson [6]) have carried out experiments on the cryogenic heat pipes. In all these investigations either the condenser is immersed in the liquid nitrogen or the condenser is connected to cryocooler whose operating temperature can be maintained at constant level by varying the cooling capacity. However, in most of the practical applications, where liquid nitrogen bath is used as cold reservoir, it is very inconvenient to immerse the heat pipe into liquid nitrogen bath. In that situation, A. Senthil Kumar *et al.*, [7], the condenser has to be connected to the cold reservoir externally. In such cases the performance of the heat pipe is expected to deteriorate as the operating temperature tends to increase.

The present experimental investigation focus on the start up behavior of a trapezoidal axial groove wick and SS wire mesh wick heat pipes with the condenser connected to the reservoir externally.

EXPERIMENTAL INVESTIGATIONS

A special liquid nitrogen cryostat has been designed and developed for testing of heat pipes. The wire mesh wick heat pipe with oxygen and trapezoidal groove heat pipe with nitrogen and oxygen as working fluids were tested at horizontal position with different heat loads. In order to compare the effectiveness of the heat pipe, an experiment was performed on the heat pipe without the working fluid. Moreover in order to get the effectiveness of the heat pipe compared to copper rod experiments were also conducted on an equivalent diameter solid copper rod. To nullify the effect of spurious heat flux in the set-up, an experiment was performed on solid copper rod instead of calculating theoretically.

DEVELOPMENT OF EXPERIMENTAL SETUP

The experimental set-up shown in Figure-2 consists of a vacuum chamber with a liquid nitrogen bath cooling system, a high vacuum pumping system and instrumentation and data acquisition system. A cylindrical liquid nitrogen vessel of diameter 200 mm and 300 mm length is welded to the top flange using a neck tube of 50 mm diameter and 80 mm length. The condenser section of the heat pipe to be tested will be attached to the bottom of the liquid nitrogen bath using clamps and screws. The top vacuum flange has two feed-throughs for connecting the leads of heater and other temperature sensors. Each feed-through has 37 pins. The feed-throughs are fixed to the top flange by screws with O-ring sealing. Heat load is applied to the evaporator section with the help of a manganin electric heater wound on the evaporator and a D.C power source.

The entire assembly of vacuum chamber and liquid nitrogen is made up of SS 304. The vacuum chamber is evacuated using an oil-diffusion high vacuum pumping system. The vacuum level in the chamber is measured using a cold-cathode penning gauge. For measuring the temperature profile of the heat pipe PT 100 sensors are used. The output of the temperature sensors and the power input to the heater are acquired by a PC using a Keithley scanner/DMM (model 2000).

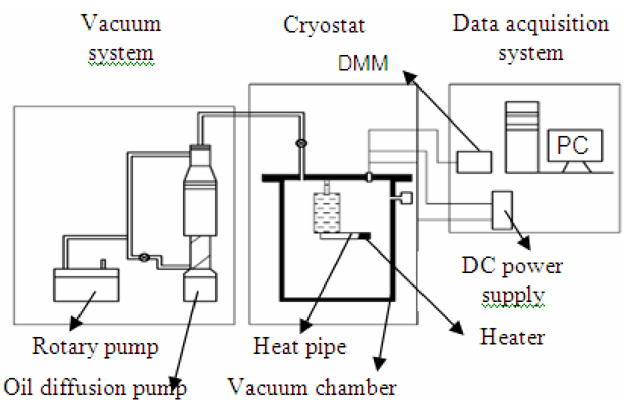

Figure-2. Schematic of experimental setup.

FABRICATION OF CRYOGENIC HEAT PIPE

Table-1 summarizes details of the heat pipe for each of the working fluid used in the present work. The axial grooves are made by EDM wire cutting method. The machined heat pipe is cleaned with a solution of 50% nitric acid and 5% hydrofluoric acid. End caps are welded at the both ends of heat pipe using argon arc welding. The fill tube is fitted into the hole provided in one of the end caps and is brazed. Initially the heat pipe is degassed for about 6 hours. Then the evacuated heat pipe is weighed. The filling is carried out by evacuating and then backfilling with charge. In order to facilitate filling, the heat pipe is immersed in a liquid nitrogen bath. The heat pipe is weighed again and thus it is ensured that the required amount of gas is filled. The fill tube is then pinched off and brazed. The mass of the charge in the heat pipe is calculated by,

$$m = V_v \rho_v + V_l \rho_l \tag{1}$$

where m is the mass of the charge, V_v and V_l are the volume of the vapour and liquid, respectively and ρ_v and ρ_l are the density of the vapour and liquid, respectively.

The SS wire mesh is wound tightly around a lengthy rod whose diameter is smaller than the vapor core diameter of the heat pipe. Then the rod along with the wick is inserted into the container. The wick unwinds and adheres tightly against the inner wall. The rod is then pulled out. The number of layers while wounding the wick around the rod is made to be slightly exceeding the actual number of layers as an allowance for the unwinding of the wick when it is released.

Table-1. Design specifications of heat pipes.

Length of heat pipe in mm	180		300
Length of evaporator section in mm	60		120
Length of adiabatic section in mm	60		70
Length of condenser section in mm	60		130
Outer diameter in mm	12.72		15.5
Inner diameter in mm	10.24		13
Type of wick	Trapezoidal groove 1.34x0.84x 0.6mm		SS wire mesh 100x100
No of grooves	17	17	4 layers
Working fluids	N_2	O_2	O_2
Amount of charge in grams	2.24	2.09	8.846

EXPERIMENTAL PROCEDURE

The condenser portion of the heat pipe is fixed to the bottom of the liquid nitrogen vessel with clamps and screws. Over the evaporator length a manganin heater is wound uniformly and spirally. Three PT 100 sensors are fixed on the heat pipe, at the condenser and evaporator ends and one at the middle. The heat pipe is spirally wound with 10 layers of multilayer insulation (Jehier, France). The liquid nitrogen vessel surface is taped with aluminum adhesive foil and then wound with two to three layers of MLI. This is carried out in order to avoid the need for frequent filling of the liquid nitrogen vessel. The system is assembled and pumped down for about one day. The vacuum level attained is 1×10^{-4} mbar. Liquid nitrogen is transferred into the liquid nitrogen vessel and allowed for the cool down of the heat pipe. After filling of liquid nitrogen the vacuum level improves to 2.9×10^{-6} mbar due to cryopumping. Then a heat load of 0.5 W is applied on the evaporator using a D.C. power supply. Data are acquired at regular intervals till a steady state is reached. Then the heat load is increased by 0.5 W. The above procedure is continued till the evaporator temperature goes above the critical temperature of the working fluid, which indicates dry-out of the evaporator.

RESULTS AND DISCUSSIONS

Start-up behavior

In practical applications such as cooling-down of large superconducting magnets, heat pipes have to be started from ambient temperatures. This presents some unique problems since start-ups occurs from the supercritical state of the working fluid. However, in this present study, in order to have an easy start up, the heat pipe is cooled completely prior to the application of heat load. In this case, the start-up occurs from the saturated liquid condition. The Figures 3, 4 and 5 shows the temperature at various sections of the different heat pipes when a load of 0.5 W is applied to the evaporator. The heat pipes are started from a sub-cooled state. Hence the start-up of the heat pipe was smooth and it can be noted from the steady state temperature profiles that the mean operating temperature of the heat pipe has increased with the increase of heat load. Hence, with the present experimental system, it is not possible to increase the heat load while maintaining the heat pipe at a constant temperature. When the heat load is increased, the operating temperature of the heat pipe also increases.

The variation of the temperature difference between the condenser and evaporator ends of different heat pipes and copper rod with heat load is shown in Figure-6. An experiment was performed on the heat pipe without any working fluid (i.e., evacuated). During this experiment the fill line was kept open and thus the heat pipe was evacuated, and heat load of 0.54 W was applied. Now, as the heat pipe is empty, all the applied heat would be transported to the condenser section by only solid conduction. In this case the measured temperature difference between the condenser and evaporator ends is 101 K. On the other hand, with the heat pipe filled with working fluid, for the same heat load, the measured temperature differences are 3 K, 5 K and 9 K for different heat pipes. This clearly demonstrates the effectiveness of the heat pipes.

The liquid pressure drop and corresponding temperature difference would be the reason for lesser performance of wick heat pipe because of imperfection of wick straightness while in operation. At the same time, during in actual operation the lengths of evaporator and condenser are varying. The reason is, when the vapor flows from the evaporator section to the condenser section it flows through some distance into the condenser due to inertia rather than condensing exactly at the starting point of the condenser. Due to this the effective length of the condenser decreases. Hence the heat transfer area of the condenser decreases resulting in decreased performance. In the evaporator section the effective length increases since actual evaporation process starts even before the working fluid reaches the evaporator end owing to conduction of heat through the material of the wick and wall.

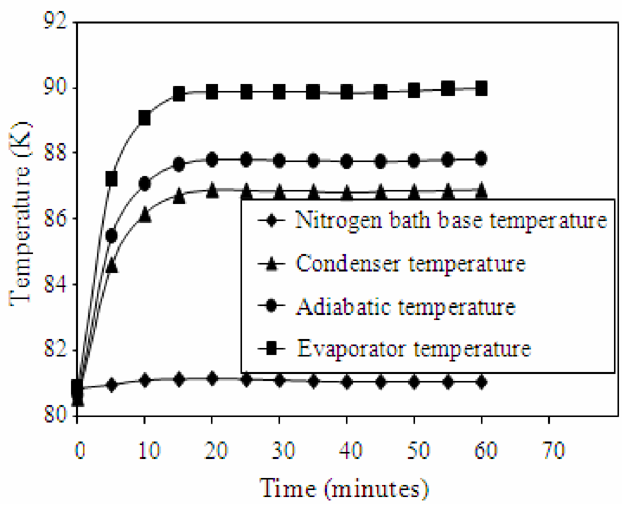

Figure-3. Start-up behavior of trapezoidal groove with nitrogen heat pipe for 0.5 W heat load.

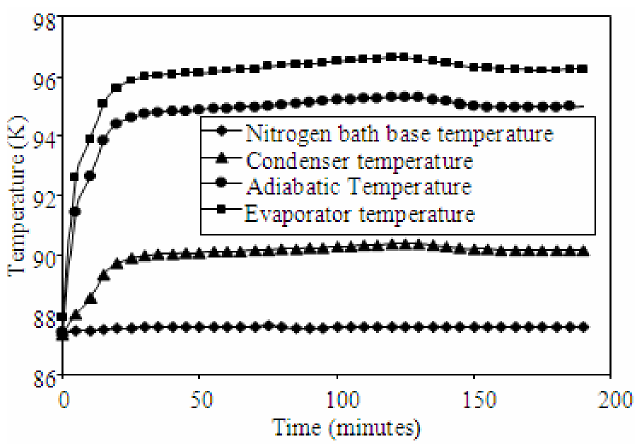

Figure-4. Start-up behavior of trapezoidal groove with oxygen heat pipe for 0.5 W heat load.

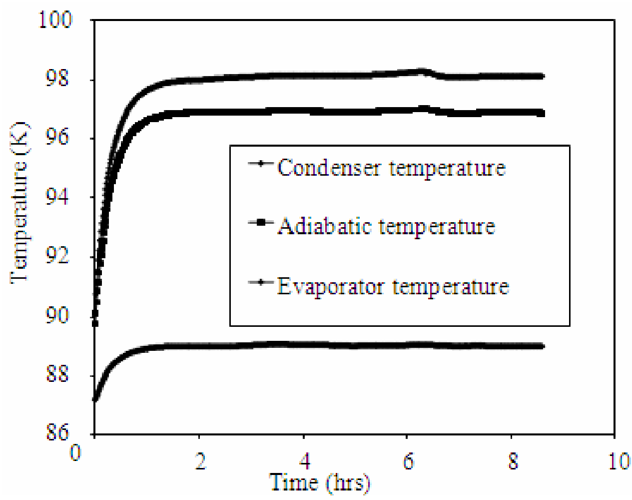

Figure-5. Start up behavior of SS wire mesh heat pipe with oxygen for 0.5 W Heat load.

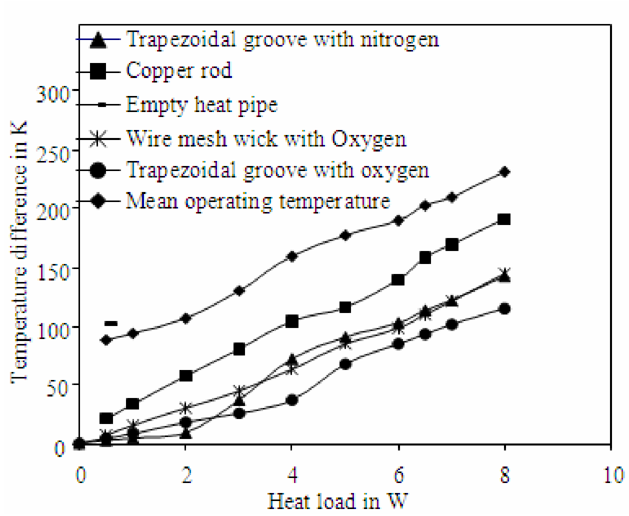

Figure-6. Temperature difference against heat load.

CONCLUSIONS

An experimental set-up for testing cryogenic heat pipes at about 77 K has been designed and developed. An oxygen filled SS wire mesh wick and an oxygen and nitrogen filled trapezoidal axial grooved heat pipe was fabricated and tested with the condenser connected to the reservoir externally. The start-up behavior and temperature difference against the heat load with mean operating temperature are discussed. The experimental result shows that the temperature difference of trapezoidal groove with nitrogen is 2.3 times lesser than SS wire mesh wick heat pipe.

ACKNOWLEDGEMENT

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